ULTRASONIC ASSISTED WATER FLOODING

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DEDICATION

"To my parents, my sister and my love *Niloofar.*

Your love and support represents the main motivation

To face new challenges and achieving my goals"

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ABSTRACT

Waterflooding being the most frequently used improved oil recovery methods fails to produce more than 30% of OOIP due to high viscosity of oil and/or high interfacial tension. Therefore chemicals or miscible flooding methods are required to improve the recovery of waterflooding. Another alternative and yet unconventional method is application of ultrasonic waves to waterflooding. Despite more than 40 years of experimental studies, there is lack of fundamental understanding about mechanisms and factors controlling the efficiency of ultrasonic assisted water flooding.

Series of displacement experiments were conducted on unconsolidated sand pack, using kerosene, vaseline and engine oil as non wet phase in the system. 2-16% increase in the recovery was observed as a consequence of sonication. In order to enhance the understanding about contributing mechanisms a series of supplementary (static) experiments were conducted by using ultrasonic bath, including: temperature experiments, emulsification experiment and one phase flow experiment. From the results of those experiments, emulsification and viscosity reduction were identified as main mechanisms contributing in improving the recovery of waterflooding.The outcome of this research is expected to enhance the insight about application of high frequency waves and reducing ambiguities about the mechanisms involved.

ABSTRAK

Banjiran air sebagai kaedah meningkatkan penghasilan minyak yang paling banyak digunakan telah gagal menghasilkan lebih daripada 30% kandungan minyak asal disebabkan kelikatan minyak yang tinggi dan/atau tegangan permukaan (interfacial tension) yang tinggi. Oleh itu kaedah banjir menggunakan bahan kimia adalah diperlukan untuk meningkatkan penghasilan minyak. Pilihan lain yang ada tetapi tidak biasa digunakan adalah aplikasi gelombang ultrasonik bersama banjiran air. Walaupun telah lebih 40 tahun kajian dan eksperimen dijalankan, masih terdapat kekurangan pemahaman asas tentang mekanisma dan faktor-faktor yang mengawal keberkesanan banjiran air diperkuatkan ultrasonik.

Beberapa siri eksperimen penyesaran telah dijalankan di dalam pek pasir menggunakan minyak tanah, vaseline dan minyak enjin sebagai fasa tidak basah (non wet phase) di dalam sistem. Kenaikan 2-16% dalam perolehan minyak telah diperolehi kesan daripada penggunaan sonik. Untuk mempertingkatkan lagi pemahaman tentang mekanisma yang terbabit, satu siri eksperimen statik telah dilakukan menggunakan mandian ultrasonik, termasuk: eksperimen suhu, eksperimen emulsi dan daneksperimen satu fasa. Daripada keputusan yang diperolehi, emulsi dan penurunan kelikatan telah dikenalpasti sebagai mekanisma utama menyumbang kepada peningkatan perolehan minyak. Hasil kajian ini dijangka akan menambah pengetahuan dalam aplikasi gelombang berfrekuensi tinggi dan menurunkan keraguan tentang mekanisma yang terbabit.

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LIST OF SYMBOLS

N_{ca}	-	Capillary number
V	-	Velocity of fluids
V	-	Velocity of waves
Σ	-	Interfacial tension
μ_w	-	Viscosity of water
μ_o	-	Viscosity of oil
kr_w	-	Relative permeability to water
kr_o	-	Relative permeability to oil
F	-	Frequency of waves
T	-	Period of waves
Λ	-	Wave length
M	-	Mobility ratio
M_{sc}	-	Critical mobility ratio
Θ	-	Angle between
R	-	Radius of pore throat
L	-	Length of the sample
A	-	Area of sand pack
P	-	Density of fluids
G	-	Gravity acceleration
H	-	Thinckness of the formation
A	-	Vibration amplitude
T	-	Temperature
$\mathrm{T_r}$	-	Reduced temperature
P	-	Pressure
Y	-	Salinity of brine

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CHAPTER 1

INTRODCUTION

When the natural drive mechanism of a reservoir is not sufficient to produce more oil, energy must be added to the reservoir to produce additional oil (Teknica, 2001). The energy is introduced to the reservoir in forms of waterflooding or gas injection. The added energy facilitates the movement of oil, providing additional recovery at improved rate. Due to availability, waterflooding has been and continues to be very successful and improves the recovery of oil from known reservoirs (Carcoana, 1992). Thomas (1989) postulated that factors such as reservoir geometry, rock properties (i.e. porosity, permeability, clay content, net thickness and fluid saturations), reservoir depth, lithology and fluid properties should be considered in order to select a reservoir as a proper candidate for waterflooding. Primary and secondary stages however are not capable of producing more than one-third of original oil in place (Ahmad, 2000; Carcoana, 1992; Teknica, 2001). The failure of waterflooding to recover the remained oil (which is about 70% of OOIP) can be attributed to number of reasons for instance: high interfacial tension, adverse mobility ratio heterogeneity.

Mobility ratio more than one represents existence of fingering in the displacing front. This may be resulted either from reduction in relative permeability of rock to the oil, high viscosities of oil or simultaneous effect of both. For light oil reservoirs efficiency of waterflooding is around 20 to 40% of OOIP and mobility control is not critical since, viscosity difference between the fluid is not that large; however in heavy oil reservoirs viscosity difference of injected water and oil is large, and water tends to channel and finger through the reservoir and leave large area of the reservoir intact. Despite all poor recoveries predicted theoretically, there have been numerous reports of heavy oil waterflooding performed in the literature (Mai and Kantzas, 2010; Ahmadloo *et al.*, 2010). It should be noted that, in all cases of waterflooding of heavy oil reservoirs, despite highly adverse mobility ratios of waterflooding some oil were still recovered. Although waterflooding of heavy oil reservoirs are performed regularly in western Canada, there is a surprising lack of information regarding the mechanisms by which water can recover viscous oil (Mai & Kantzas, 2010). Therefore increasing the recovery of waterflooding in heavy oil reservoirs is of great importance.

Entrapment of the remaining oil in the interstices or pores of the rock is mainly due to capillary forces which exist between two immiscible phases i.e. high interfacial tension (Melrose & Brander 1974; Carcoana 1992). Interactions between capillary and viscous forces govern phase trapping and mobilization of non-wetting phase. In the reservoir the discontinuous trapped phase (i.e. oil) cannot be mobilized unless capillary force can be exceeded by viscous forces. Dimensionless index called ‘capillary number’ was introduced to express the ratio of viscous to capillary forces. It is in direct relationship with microscopic displacement efficiency and therefore recovery (Lake, 1996), the most common type of capillary number is the one proposed by (Saffman & Taylor, 1958):

$$N_{ca} = \frac{v\mu}{\sigma} \qquad (1\text{-}1)$$

For normal waterflooding the capillary number is in order of 10^{-7} to 10^{-6}. Manipulating interfacial tension is the best way to achieve effective capillary numbers or in the other word improved recovery. Using chemical and miscible flooding has been known as conventional method to increase the recovery by reduction or elimination of interfacial tension.

Elimination of capillary force may be achieved through use of chemicals. This methods of enhanced oil recovery are characterized by the addition of chemicals to water (alkaline, surfactant, polymer or combination of each) in order to generate fluid properties or interfacial conditions that are more favorable for oil displacement. Both displacement and sweep efficiency are affected by chemicals (Green, 1998). Although just like any other method they are suffering from some drawbacks. The main issue of utilizing chemicals, which are often costly materials, is adsorbtion. Besides partial sweeping of a reservoir due to gravity segregation, environmental concerns, injectivity issues and incompatibility with rock and fluid are common problems associated with using chemicals (Carcoana, 1992).

CO_2 flooding is said to be the most promising method among miscible flooding methods (Teknica, 2001). It eliminates interfacial tension by creating miscibility between two fluids if required conditions of miscibility can be achieved (minimum miscibility pressure). Unlike chemicals it only improves displacement efficiency. The dominant issue concerning use of CO_2 is its mobility control i.e. fingering. In addition to that availability of CO_2, transportation, loss of miscibility due to injectivity problems and formation of hydrates in some cases are the problems of CO_2 miscible flooding (Donaldson, 1985). Kleppe (2008) thoroughly explained the complications of implementing CO_2 in the North Sea reservoirs.

Thermal recovery is the principal method for recovery of heavy oils. It is introduced to reservoir in forms of hot water, steam injection and in-situ combustion. The most dominant mechanisms by which thermal methods increase the recovery is reduction of viscosity and lowering interfacial tension which is resulted from increasing the temperature of the reservoir. Cyclic steam simulation, to a large degree, suffers from bypassing and channeling. On the other hand in-situ combustion is highly sensitive to crude oil and rock properties (Guo, 2009). The failure of most in-situ combustion field operations is due to difficulties in controlling combustion front advancement. Steam flooding, which is the most efficient method among thermal methods, is suffering from channeling and gravity override which results in early breakthrough (Teknica, 2009).

In all the above mentioned enhanced oil recovery methods, means of delivering the energy to the reservoir is via hydraulic fluid. Therefore they are suffering from problems such as bypassing and channeling as fluids always choose the path of the least resistance. Hence, many EOR methods fail in heterogeneous formations, leaving large volumes of oil behind.

1.1 Seismic Waves

Seismic waves are waves of energy that passes through the earth, for instance as a result of an earthquake, explosion, or some other process that emits low-frequency acoustic energy. Acoustic energy propagates in all directions, and is unaffected by the pore network or permeability of the formation (Hamida, 2006). Thus, it is possible to influence every point in the reservoir simultaneously, and obtain the maximum efficiency at all times (Beresnev and Johnson. 2005). Seismic waves have been used in petroleum industry in several applications including well logging, well stimulation, and as a method for increasing the recovery of oil for more than forty years (Westermark, 2001). High frequency (ultrasonic) is a type of wave having a frequency above 20 *KHz*.

Efforts are made to develop alternative methods to conventional methods due to the fact that conventional methods may not be applied to all type of reservoirs, as each of them has its own limitation in terms of type of rock, fluid or conditions of application. One of these alternatives is the application of ultrasonic waves to the reservoirs. Further Advantages of application of ultrasonic waves over conventional methods are: Applicability without interrupting production, Elimination the need for chemicals and Possibility of influencing all point of reservoir (Hamida, 2006).

Nikolaevskiy (1996) explained that fluid-bearing sands can change the frequencies of seismic waves. Ultrasonic waves are generated as a result of low-frequency oscillation in porous media. Moreover, high frequency waves have short wavelengths and significantly contribute to mechanical perturbation at the pore scale; this dominant frequency depends on the size and the compactness of grains and the fluid saturation. High wavelength elastic vibration, on the other hand, only influences the bulk behavior of the porous solid. Consequently, although ultrasonic stimulation may be considered a "secondary" driving mechanism, it still has a great impact on the overall performance of field applications (Hamida, 2006).Mechanisms by which seismic waves affect the recovery of oil are explained by various researchers:

- Propagation of waves in medium make particles vibrates alternatively and causes the stress and acoustic pressure to change periodically (Guo et al. 2009).

- When the compression occurs, the bubbles implode, as a result, tremendous pressures are produced that may reach several thousand atmospheres. The induced pressure gradient can contribute in percolation of oil bubbles, increasing capillary rise and increasing the recovery. This effect is called cavitation (Duhon &Campel, 1965; Hamida, 2006; Naderi and Babadagli, 2008).

- Reduction of capillary forces due to the destruction of surface films generated across pore boundaries (Hamida, 2005; Amro, 2007; Cindoha, 2007).

- Mechanical deformation of the pore walls, and consequently changes in permeability and porosity (Ariadji, 2005; Cindoha, 2007).

- Increase in relative permeability of the phases. (Beresnev & Johnson, 1994) (Hamida, 2005).

- Heating the oil, causing its viscosity to decrease. (Duhon &Campel, 1965; Ariadji, 2005; Cindoha, 2007; Guo et al., 2009).

Above mention mechanisms of ultrasonic waves in reduction of viscosity and interfacial tension make it a good option to be applied in combination with water flooding to improve oil recovery.

In a pioneering research Duhon & Campbell (1965) conducted research on applications of ultrasonic wave to a waterflooding on the sandstone cores. Their research is one of the most comprehensive investigations to date, although it has some deficiencies. They conduct their experiments using ultrasound waves in range of 10 - 55 *KHz*, to long and short cores, using three different fluids to investigate the effects of viscosity by using ultrasound waves. They concluded that lower frequencies result in better recoveries due to lower attenuation. They also attributed increase in the recovery to cavitation phenomena which resulted from presence of gas bubbles in the liquid. This conclusion was not totally convincing as they did not design any other experiment to investigate recovery without cavitation mechanism to confirm their theory. They used core test fluid, diesel oil and engine oil to represent oil in the system and concluded that recovery is better in less viscous fluid being core test fluid.

Series of experiments were conducted by Hamida & Babadagli (2005-2006) on the effects of ultrasonic waves on capillary displacement as well as miscible and immiscible displacement in porous media. More details of their work are provided in chapter two of this research.

Amro *et al.* (2007) conducted experiments to investigate the affectivity of ultrasound waves on mobilizing of additional oil. The experiments were conducted on Berea sandstone and using Saudi crude oil having the viscosity of 13-16 cp. The cores were tested horizontally and vertically to represent the effects of gravity on oil recovery in presence of ultrasound waves operating at the frequency of 15 KHz and intensity of 300 watts. They also concluded that ultrasonic waterflooding is more effective in depleted reservoirs.

There has been an increasing interest in the application of ultrasonic to waterflooding in heavy oil around the world, especially in China and Canada. Guo, (2009) explained mechanisms by which ultrasound waves improve recovery. They also conduct experiments to show effects of ultrasonic waves on viscosity and realize that the viscosity is reduced due to exposure to ultrasound waves but this effect was temporary.

1.2 Problem Statement (Research Questions)

The research will be answering following questions:

1. How much is the recovery of waterflooding with or without ultrasonic stimulation?

2. How do different oils (in term of viscosity) respond to ultrasonic waves?

3. What are the mechanisms of ultrasound which result in improvement of flow?

1.3 Research Objectives

The objectives of this research are:

1. To measure recovery of oil by waterflooding in presence of sonic waves (ultrasonic assisted waterflooding) and compare it to straight waterflooding flooding (without ultrasonic).

2. To investigate effect of different viscosities of oil on ultrasonic recovery.

3. To find mechanisms of ultrasonic by which recovery is improved.

1.4 Research Scope

This research investigates the effects of ultra sonic waves on the recovery of oil in a sand pack model. The focus of study will be waterflooding of viscous oil in presence of ultrasonic waves in low capillary numbers. Sand pack is 92cm long by 3.8cm in diameter. The porosity is around 33 and the permeability is around 4 Darcy. An ultra sound generator with 40 *KHz* frequency and power output of 100-500 W/cm^3 is manipulated according to the type of experiments. The working fluids are:

kerosene (viscosity of less than 1 cp), vaseline (22 cp) and engine oil (243 cp) and brine with 3% (30000 ppm) Nacl.

1.5 Significance of Findings

The results of displacement experiments are expected to quantify the effects of ultrasonic waves on recovery of different fluids. The static experiments will be helpful in identification of contributing mechanisms in ultrasonic applications. Therefore this study seeks to obtain more insight about mechanisms by which ultrasonic waves affects rock and fluid properties; this eventually helps in clarifying the ambiguities which hamper the larger scale applications of ultrasonic waves in the industry.

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